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EXPLOSIVES RESEARCH AND DEVELOPMENT ESTABLISHMENT

TECHNICAL NOTE No. 86

The Scope and Methods of Environmental Testing of Double-Base Propellant Rocket Motors: Choice of Conditions and Interpretation of Results

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SUMMARY

Environmental testing problems are considered, primarily from the standpoint of the propellant chemist. Environments are defined and the significant aspects of motor design and possible failure modes considered. Preliminary tests, and environmental tests proper, which aim to simulate storage, transport and handling hazards in a realistic manner, are discussed, together with the size and scope of a test programme. In conclusion the importance of surveillance is emphasised, in order that the results of these programmes can be checked and adequate reasons established to account for any failures.

FOREWORD

This memorandum is the text of the paper presented by Dr J Gooding at the Institut fur Chemie der Treib-und Explosivstoffe Annual Symposium, Karlsruhe, Germany, 27 - 29 September 1972.

CONTENTS

SUMMARY

Environmental trials of double-base rocket motors remain simple in conception. Tests to simulate terrestrial environments consist basically of storage at selected uniform (often elevated) temperatures, and of cycling between suitable upper and lower temperatures. Tests to simulate transport and handling hazards are essentially realistic in that they reproduce expected impacts, vibrations and other likely conditions to which the motor (packed or unpacked) may be exposed.

The art of programming environmental trials lies in the selection of conditions which will determine critically whether design requirements have been met, while ensuring that the trials do not produce invalid results, ie unrealistic types of failure.

Because of the costs of both providing motors and testing them it is usually impossible to obtain results which are as significant, statistically, as could be desired. It is therefore necessary to ensure that all possible information is recorded about the motors - of their manufacture and of inspections during and after the trials, in order that, wherever possible, adequate reasons can be established to account for any failures.

Reference: WAC/222/020

INTRODUCTION

Rocket motors often form part of devices which are both sophisticated and expensive. The need to be satisfied about their reliability is therefore paramount. Motors themselves cannot be considered cheap and there is the added expense of providing and using facilities for testing them. These considerations prompted a careful look at various aspects of the problem of obtaining maximum value for time, effort and money expended in getting a rocket motor designed, manufactured, tested and accepted for service. This paper deals with some of the consequences as they affect environmental testing.

A motor is designed in response to a stated requirement which will detail such things as performance, and its limits, the environmental conditions under which the performance must be realised, and the length of time during which the motor should remain serviceable.

An early source of misunderstanding lay in the terms in which the environmental conditions were defined, and the interpretations placed upon them in devising suitable tests. Thus the dangers of stipulating "world wide" conditions is that testing may well become unduly severe. When the inevitable failures occur, questions are asked about design modifications, with their implications about penalties in the form of extra time, money and effort. It became evident that the more closely could expected environments be defined, the greater would be the chances of designing suitable tests, and the higher would be the chances of avoiding the penalties mentioned above. It was realised too that designing for an unnecessarily wide temperature range may entail a severe penalty performance-wise.

Another important part of the problem was that to test sufficient numbers of motors to obtain statistically significant assurances about quality is almost certain to be prohibitively costly, in terms of proportions of stocks diverted from their prime role, and allocations of limited test space and facilities. These difficulties can never be entirely surmounted but the consequences can be minimised by collecting as much information as possible - both about the motors being tested, before and after test, and about previous testing of similar motors.

This paper examines environmental testing problems primarily from the standpoint of the propellant chemist. Certain safety questions of interest to the design engineer which originate in the behaviour of the whole complex and which come within the scope of environmental testing have not been considered here.

DEFINITION OF ENVIRONMENTS

Defining environments has become rather easier in recent years as there has been a useful rationalisation (in UK) which divides up world climates into nine types. These begin at the hot end of the temperature spectrum with Hot Dry (tropical desert) and Hot Wet (tropical jungle) and continue through Intermediate (temperate) to Cold and Extreme Cold (continental tundra). Maximum and minimum temperatures have been assigned to all these types ("exceeded on only

1 per cent of occasions"). Additionally, on the basis that maxima and minima are likely to be associated with seasons of the year, similar extreme cycles associated with these maxima and minima (and with the intermediate stages) have been defined together with their relative frequencies (days per year). Thus the most extreme of the hot climates is associated with maximum temperatures of 52°C (shade) and 71°C (with full benefit of solar radiation), which are themselves associated with extreme (hot) diurnal cycles of 33/52°C and 33/71°C respectively for 7 days out of a year, and with cycles of lesser severity on relatively more occasions.

Similarly, at the cold end of the spectrum, a temperature as low as -57°C may be expected (exceeded on only 1 per cent of occasions). There are cold diurnal cycles to match, and other cycles with lesser cold, on more frequent occasions.

At the cold end, a special allowance may have to be made for altitude effects in connection with carriage in aircraft which are not equipped with heated storage space, when the question of kinetic heating (at supersonic speeds) does not arise.

The main reason for emphasising here the extreme hot and cold ends of terrestrial environments is that these are the ones likely to be of greatest significance in governing the life and reliability of rocket motors.

The next step in the definition of environment is to make estimates of how a motor is likely to spend its service life. The very high cost of the devices in which they are used has forced users to consider logistics in much greater detail than heretofore. The form in which the logistic analysis is now appearing comprises estimates of the lengths of time in which the devices are likely to spend in magazines (which are usually now air-conditioned) and the probable total extent of their deployment in conditions which are accepted as being definable by the nine types of climate referred to above.

Obviously there can be no final and binding guarantees that the envisaged environmental test programme will truly represent the ultimate reality, but the analysis nevertheless gives an extremely useful working basis for devising storage tests. It will sometimes be possible to 'build-in' a modest margin of overtest and so increase confidence. Ability to do this will depend to a considerable extent on what assurances have been obtained from previous work.

Transport and handling environments also need to be considered. The logistic analysis will take into account the circumstances and methods of transport, ie whether by road, rail or air, or by a mixture of these, and how often. The hazards associated with transport movements, such as vibration, bumping, dropping, and accidental exposure to rain are well understood and tests can readily be devised.

A rocket motor could be part of a larger assembly, or separate. It could be packed or unpacked. The logistics should make these matters clear. The trials will then evaluate packages as well as the motors themselves.

SIGNIFICANT ASPECTS OF ROCKET MOTOR DESIGN AND POSSIBLE FAILURE MODES

A rocket motor consists basically of an outer metal, or possibly fibre glass, assembly, usually cylindrical in shape, containing a fairly close-fitting cylindrical charge of propellant. This propellant could be double-base, or composite. The charge may be unperforated (end-burning), but is more usually tubular (radial burning).

If the charge is loose, ie not case-bonded, it will probably be inhibited on its cylindrical surface by a carefully bonded sheath of a suitable non-metallic material. If it is bonded, the bonding will comprise a rather similar cylindrical sheath of non-metallic heat insulating material secured by adhesive on its outside to the hardware and on its inside to the propellant, which will always, in these circumstances possess an internal conduit.

The size and shape of the whole motor are dictated essentially by the total impulse required, the time during which this impulse is to be delivered and by aerodynamic requirements. In addition, there will be a suitably placed igniter consisting of a small container, usually of metal filled with some pyrotechnic composition. The assembly will include some small electrical igniting device which has leads which generally pass through the venturi closure. The igniter usually needs some sort of metal foil closure, to act as a blow-out window. There is a danger that too tough a closure will produce an explosion in the igniter - not a flame.

Before a critical environmental test programme can be devised, and limits set to the test conditions, the nature and incidence of the various possible failure modes must be thoroughly understood. As they are generally widely known already and accepted they will be dealt with very briefly here, extra detail being given only where necessary for purposes of illustration. They relate primarily to double-base propellant motors, the subject of this paper, but some of them are equally relevant to composite propellant motors.

Loss of Chemical Stability

This has been studied through loss of stabiliser, in separate trials on the propellant. There is usually an ample reserve of stabiliser in most propellants.

Fissuring of Propellant by Gas Formation

Separate trials on propellants usually establish what thicknesses can be maintained at what temperatures without formation of gas bubbles, a fault which should be reckoned uncharacteristic of service conditions.

Self-heating

This can end disastrously in 'cook-off'. From separate propellant trials, the risk can be largely discounted in propellant charges used in tactical weapons. A special case for consideration is where there are specially hot environments, eg near aircraft engines.

Deterioration of Mechanical Properties with Ageing

This can affect functioning critically at high temperatures, due eg to collapse of a tubular grain.

Thermal Stresses

These arise in non-metallic materials of low thermal conductivity which are subjected to temperature gradients. Bonded assemblies also develop stresses both in the materials themselves and in the bonding when subjected to changes in temperature. Characteristic examples of stress failure could be simple unbonding of the inhibition or cracking at the conduit surface of propellant in a cooled case-bonded motor. A more complex example would be a similar failure - but only after the propellant had aged (see previous heading).

Changes in Ballistics

This could be an undramatic drift of ballistic parameters to outside specification, but there might be a deterioration in motor performance which could be crucial in some respect.

Failure of Inhibition

Inhibition which bonds well often tends to absorb nitroglycerine from the propellant, which could be reflected as 'burn-through' in ballistic tests. Too high a storage temperature can promote other effects eg cracking of inhibition and unbonding, which are likely to be uncharacteristic of normal service.

Materials Compatibility

Gassing tests at 80°C on small mixed samples of propellant and material are normally carried out beforehand, so this aspect is usually safeguarded. Gassing in a motor could produce unwanted new surfaces and cause ballistic failures. Other lesser troubles can also occur.

Penetration by Moisture

Moisture, from rain or high humidity, could penetrate the sealing of the motor and/or a packing box and cause trouble through unwanted internal interactions, affecting propellant or igniter composition, mainly ballistically.

PRELIMINARY TEST WORK

Before environmental tests can be embarked upon with the proper degree of confidence, it is helpful to be in possession of the results of many preliminary research and development tests - on materials (eg propellant and inhibition etc) and on prototype assemblies relevant to the final design of motor.

Many of these tests are much accelerated eg at 80°C or over. Some of them were touched on in the previous section where reference was made to chemical stability of propellant, to gassing and 'cook-off' and to compatibility with non-explosive materials.

There are other somewhat longer-term development tests (at say 50-60°C) on the propellant especially, which throw light on the likelihood of changes, in such important properties as physical behaviour and rate of burning, with ageing. Trials of this class are also applied to inhibition, in sandwich tests with propellant, in which such matters as nitroglycerine migration and changes in inhibitor strength may be studied.

Mention must also be made of the special question of the effect of solar radiation on external paint on motors and their packing boxes. In this case, the test environment must be one not just of heat but include radiations of suitable wavelength. Ability to reflect heat and resist ordinary weathering need to be studied.

There remains another facet of this work in which accelerated tests are done - on motors themselves or suitable assemblies, ie with propellant, inhibition and hardware all present. This class of work is usually regarded as part of motor development and embraces essentially temperature cycling trials. These are usually much more severe than those mentioned in the section above about environkents. It is often found that a genuine motor may be safely cycled between the top temperature of the hottest environment and the bottom temperature of the coldest. A common test is twelve such cycles, spread over 24 days, which may be considered as more severe than the separate hot and cold series of cycles now being proposed as part of the more realistic tests.

Another test of a similar kind, slightly more sophisticated, and known as the Williams test, consists of a preliminary period of heating (say several weeks at 60°C) to simulate the condition of an 'aged' motor, followed by cycling of the kind already mentioned. The top and bottom temperatures of the cycling may be hot and ordinary ambient - or ambient and cold respectively, depending upon details of the design under test, or might embrace the whole design temperature range.

Considerable discretion must be used in applying cycling tests to case-bonded motors because the thermal stresses can soon become intolerable. There is usually no scope for any accentuation of the severity of the test beyond that implied by the design requirements, which in the nature of things tends to be limited.

ENVIRONMENTAL TESTING

If all the tests described in the section above have been brought to a successful conclusion, which implies that all the judgments about a new motor design based on the preliminary work are sufficiently favourable, it is then possible to proceed to the environmental tests proper.

These may be considered under two headings, the thermal environment and the transport and handling environment. Climatic environment falls across both the above headings and gets dealt with indirectly under both.

Mention can be made here of the actual technique of doing thermal environmental trials. The set-up is simple in conception, amounting, as far as constant temperature experiments are concerned, to a thermostatically controlled chamber which will be mounded or sited at a safe distance. Thermal cycling is a modern addition which imposes the need for more sophisticated control apparatus. The whole can be monitored by a remotely-situated trace on a recording chart.

For these thermal trials, a summation is required of ambient temperatures and their durations. As far as pure storage is concerned, the temperatures may well be averages representing a small range. Deployment temperatures however may entail consideration of cycles of greater amplitude.

If use is made of the now well-known and accepted factor (about 2.9 per 10 degrees Celsius) that relates rate of chemical ageing of propellant to temperature of storage, then it is possible to equate much of the expected thermal environment, especially storage, to a period of time at a reference temperature. The so-called diurnal cycles of the rationalised environments can also be reduced in the same way, but the intention at the moment is to employ them (or some of them) in trials. A good reason for this is that it is possible to impose a 'skin' temperature on the motor and make it hotter or colder than the rest of the mass, a condition which is very likely to be met in service. Skin heating is usually a consequence of solar radiation.

The relatively steady-state (or magazine storage) part of the thermal environment can be translated into longer or shorter periods of time at lower or higher constant temperatures. The art of staging an environmental trial is to choose the storage temperature wisely. This can be as reasonably high as possible (at 50°C, say), subject always to the requirement that it does not induce unrealistic failures like gas bubbles in the propellant. There are instances of misjudging this possibility because insufficient allowance was made for the adverse effect case-bonding has on the incidence of gas fissuring.

There may be some useful guidance from trials on earlier designs of motor. There are instances of good results after 2 years at 50°C which is reckoned to be a 'severe' equivalent storage condition in comparison with many design requirements.

The reason for choosing as high a temperature as possible (50°C or over) is to obtain some sort of answer as soon as possible. There is a growing feeling in UK however that such trials need to be supplemented by longer term confirmatory trials at lower temperatures; 32°C and 40°C have had some support. The need for ordinary terrestrial temperatures became more obvious when case-bonded motors came to be considered. Whilst accelerated thermal ageing has its place in the development of such motors, the realisation that failures can be produced by cooling led to the notion that only a realistic environment could produce a valid result for this type of motor. Accordingly, a 'storage-year' comprising elements of temperature cycling within a larger pattern of cycling has been produced. The year contains one month of tropical cycling, a month of Arctic cycling and ten months representing gradations in a temperate climate. There would be scope for adjustment of these conditions, depending on what upper and lower temperatures are in the design requirement.

The tests of the handling and transport environment are usually sequential in nature, and essentially realistic. The numbers of motors required can be kept to a minimum by proper inspection between tests, which include impact, drops, stacking tests and the like. The transport environments are usually reduced to vibration tests, at both low and high frequency. These tests are based on measurements that have been made in typical transport media. The test machines produce sinusoidal vibrations essentially, although there are signs of a need for more 'peaky' shapes (giving a higher 'g' factor) in some instances.

Certain other tests in this class pertain more nearly to those of climatic or thermal environment. A realistic water-spray test has been devised to simulate the condition in which motors (or other items) in transit, have been unloaded on an open site and are caught in a rainstorm. Another test of the climatic kind consists of a weekly cycle that embodies an accentuation of tropical diurnal variations. It is based on alternations between 46°C/95% RH and ambient (with

condensation) and has a small element, each week, of dry heat to simulate tropical desert. This trial is known as the Intensified Standard Alternating Trial (ISAT) and has variants with different upper temperatures, ie ISAT (A) at 60°C and ISAT (B) at 75°C.

Although such a trial might seem ideal as a climatic test, objections to it are the difficulty of evaluating it thermally, because of the pronounced cycling element, and the possible dangers of the top temperature (75°C for ISAT (B)). It was originally designed for application to ordnance ammunition and small arms, not rocket motors, and it now seems that its more significant role is that of testing the sealing of joints. It also pin-points failures such as corrosions and other undesirable chemical interactions which may be promoted if the motor "breathes". It has been of special value as a test of igniter designs because of the potentially bad effects of moisture on igniter compositions.

The last test of this class provides a low pressure/low temperature environment which simulates transport in certain types of aircraft. This test may also have an element of cycling to see if "breathing" can be induced.

Assessment of the effects of environmental trials is essentially by static firing after careful non-destructive (including visual) inspection. Critical destructive inspection also plays its part. Greater emphasis is generally placed on the results of firing at the extremes of the design temperature range (rather than at 'ambient') because at each end of the scale there are factors which could play specially significant roles in causing failures. This matter is too complex to consider in detail here, but two examples will serve as illustrations. At the top end of the temperature range, physical deteriorations could cause collapse of the propellant and spoil obturation arrangements. At the bottom end, too much mismatch of, say, physical properties could produce cracking of propellant and unbonding of insulation or inhibition. It could be argued that final proof ought to be a flight test. Although there are a number of instances in which it has become clear that static firing may not always reveal shortcomings seen later in flight, it is to be hoped that flight requirements can ultimately be "built into" static firing proof, and that the advantages of measuring the static ballistic parameters outweigh other objections to this form of proof.

THE SIZE AND SCOPE OF AN ENVIRONMENTAL TEST PROGRAMME

There can never be enough motors (except possibly those of the smallest sizes) or test space or facilities available, for trials of the kind described. Provision of motors for trial purposes only is usually seen by the user as a levy on his stocks. Tests usually have to be pushed forward at a time when production snags have not all been identified. This means that the level of quality of motors set aside for test may not necessarily represent the level of quality of the eventual bulk population.

The only way to minimise the disadvantages of this situation is to build up a body of information - about propellants, about basic design arrangements and about trials on motors themselves. It is helpful for instance to have information about a propellant which has been used in an earlier design of motor - if possible of rather similar design to the new one under consideration. Some idea of the range of properties to be expected from a propellant manufactured as a series of discrete lots under large-scale process conditions can be of great

value in making decisions about a new motor.

Careful non-destructive inspection of each individual motor before and after test is an essential. Visual inspection by an experienced eye should not be underrated. Documentation of each motor should ensure that any special features or variations in make-up are recorded. Ballistic results should include time-traces as they can be an important part of the evidence needed to explain functioning abnormalities.

The skill in coming to the best conclusion about the results of trials on limited numbers lies not only in interpreting the bare details of the results, such as they are, but in producing where necessary reasonable explanations of the abnormalities. This is a task calling for experience in making maximum use of all available facts which may have some bearing on the situation. It is rarely possible to mount further trials to test whether explanations are sound because of the cost in money and time. To make further progress it may be necessary to wait a long time to examine motors which have aged naturally in Service.

SURVEILLANCE

Surveillance programmes, which entail withdrawing small samples of motors from bulk stocks as they become aged are aimed at obtaining confirmation of the results of accelerated testing. Assessment of service life can be more realistic than hitherto. This aspect can often be clarified by the staging of short mildly-accelerated trials of old motors. Surveillance also provides opportunities for checks later at less overall cost, on aspects which were not adequately dealt with in the original environmental tests.

Feed-back of information from 'in service' inspections may well be invaluable to designers who may wish to introduce late improvements to old designs or modify new designs. As an illustration of the value of surveillance, it was only through such action that a long-term incompatibility, an undesirable chemical interaction that had a long induction period for special reasons (a slow diffusion of one reactant) was discovered in a small rocket manufactured and used in large numbers by the UK during World War II.

CONCLUSIONS

The basis of maintaining a stock of serviceable motors lies in the confidence that can be built up over the years by carrying out assiduously the test, inspection, investigatory and surveillance procedures outlined above, and taking such actions as may be dictated by the conclusions reached.

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Gooding J
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